

# Interdisciplinary Aspects of High-Energy Astrophysics

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**Abstract** Modern astrophysics, especially at GeV energy scales and above is a typical example where several disciplines meet: The location and distribution of the sources is the domain of astronomy. At distances corresponding to significant redshift cosmological aspects such as the expansion history come into play. Finally, the emission mechanisms and subsequent propagation of produced high energy particles is at least partly the domain of particle physics, in particular if new phenomena beyond the Standard Model are probed that require base lines and/or energies unattained in the laboratory. In this contribution we focus on three examples: Highest energy cosmic rays, tests of the Lorentz symmetry and the search for new light photon-like states in the spectra of active galaxies.

## 1 Introduction

High energy astrophysics is nowadays a very interdisciplinary research field which either uses input from or provides new output to other fields including astronomy, cosmology, particle physics and even philosophy and (astro)biology. Examples very this becomes especially obvious includes the use of active galactic nuclei to probe the formation of structure at very high redshift of order ten, high energy cosmic rays as probes for the annihilation or decay of dark matter and the use of “standard candles” such as exploding white dwarfs and (more recently) gamma-ray bursts to probe the expansion history of the Universe.

A particular problem that sometimes occurs at these intersections are different languages spoken by the different communities. In general, however, a lot of progress has been made in that respect. This is the case in particular in astroparticle physics, a still young but meanwhile well established research discipline in its own

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right. This can be seen not least from the fact that funding agencies in most countries have developed programs and instruments aiming in specifically at this field.

The present paper can naturally cover at most a tiny fraction of interesting examples for such interfaces between neighboring research fields. We specifically focus on three topics at the interface between astronomy, high energy astrophysics and particle physics: First, ultra-high energy cosmic rays, traditionally understood as particles with energies above  $10^{18}$  eV, have been observed with energies up to a few times  $10^{20}$  eV, which is a macroscopic energy of about 50 Joules, presumably of just one elementary particle. Therefore, very likely, the sources of these ultra-energetic particles have to be exceptionally powerful and visible in other wavelengths and channels. The search of these sources has thus a strong relation to astronomy.

Second, the macroscopic energies of these particles makes them natural test beams for particle physics at energies that cannot be achieved in the laboratory in the foreseeable future. In particular, tiny violations of fundamental symmetries of Nature, such as the Lorentz symmetry, may become magnified at large energies. We are still lacking a description of gravity that is consistent with quantum mechanics and the way gravity unifies with the electromagnetic, weak and strong interactions may only manifest itself at energies approaching the Planck scale. In this case, high energy astrophysics may be an indispensable tool for the phenomenology of quantum gravity.

Finally, at the opposite, low energy end, new physics may also exist in the form of very light particles that may morph into photons and vice versa. The strongest constraints on such possibilities that are often motivated by models of fundamental physics such as string theory and loop quantum gravity often come from astrophysical and cosmological observations which offer the largest baselines and the highest energies.

## 2 Astronomy with the Highest Energy Particles of Nature ?

The research field of ultra-high energy cosmic rays started in 1938 when Pierre Auger proved the existence of extensive air showers (EAS) caused by primary particles with energies above  $10^{15}$  eV by simultaneously observing the arrival of secondary particles in Geiger counters many meters apart [1]. Since that time, ultra-high energy cosmic rays (UHECRs) have challenged the imagination of physicists and astrophysicists alike. The first cosmic ray with energy above  $10^{20}$  eV was discovered by John Lindsley in 1963 at the Volcano Ranch Observatory [2]. The record holder is probably still the famous “Fly’s Eye event” of  $\simeq 3 \times 10^{20}$  eV [3] and quickly, scientists were looking for astronomical sources [4]. Around the same time, the Akeno Giant Air Shower Array (AGASA) caused excitement because it observed an UHECR spectrum continuing seemingly as a power law around  $10^{20}$  eV. This was contrary to expectations because the famous Greisen-Zatsepin-Kuzmin (GZK) effect [6] predicts that nucleons loose their energy within about 20 Mpc above a threshold of  $\simeq 6 \times 10^{19}$  eV [7] due to pion production on the cosmic mi-

crowwave background which is a relic of the early Universe. As long as we do not live in a strong over-density of UHECR sources, this would predict a strong suppression of the UHECR flux above that threshold, often somewhat misleadingly called the “GZK cutoff”. Meanwhile, a flux suppression consistent with the GZK effect has been observed by the more recent High Resolution Fly’s Eye [8] and Pierre Auger [9] experiments and it is likely that the AGASA spectrum was due to an overestimate of the UHECR energies.

These more recent, higher statistics data, however, raised other, no less interesting questions: For the first time, the Pierre Auger Observatory which observes the Southern hemisphere from Argentina has accumulated enough statistics at the highest energies to see signs of anisotropy: A significant correlation with the 12th edition of the Véron-Cetty and Véron catalog of nearby AGNs was observed for events with energies above 56 EeV [10]. This is very suggestive because it is also the energy scale above which the GZK effect limits the range of primary cosmic rays to  $\sim 50$  Mpc. This does not necessarily mean that these objects represent the sources, but it suggests that the real UHECR sources follow an anisotropic distribution that is similar to nearby AGNs. This may not be surprising if the sources are astrophysical accelerators which follow the local large scale structure. Unfortunately, with accumulation of more data, these correlations have weakened [11]. The fraction of events above 55 EeV correlating with the Veron Cetty Catalog has come down from  $69^{+11}_{-13}\%$  to  $38^{+7}_{-6}\%$  compared to 21% expected for isotropy. If one divides the sky distribution into a component correlating, for example, with the 2MASS redshift survey and an isotropic component, this corresponds to a relatively large isotropic fraction of 60–70% [11]. Still, an excess of correlations is seen with 2MASS redshift survey at 95% confidence level. On the other hand, in the Northern hemisphere, the HiRes experiment has not seen any correlations [12].

The nature and location of UHECR sources is thus still an open question in which general theoretical considerations play a significant role. Accelerating particles of charge  $eZ$  to an energy  $E_{\max}$  requires an induction  $\mathcal{E} \gtrsim E_{\max}/(eZ)$ . With  $Z_0 \simeq 100 \Omega$  the vacuum impedance, this requires dissipation of a minimal power of [13, 14]

$$L_{\min} \simeq \frac{\mathcal{E}^2}{Z_0} \simeq 10^{45} Z^{-2} \left( \frac{E_{\max}}{10^{20} \text{ eV}} \right)^2 \text{ erg s}^{-1}. \quad (1)$$

When expressing the square of the product of the magnetic field in an accelerator with its size in terms of a luminosity, this condition can be expressed in terms of the Hillas-criterium [15] which states that the gyro-radius of a charged particle at the maximal acceleration energy must fit within the accelerator. Eq. (1) suggests that the power requirements are considerably relaxed for heavier nuclei which is easy to understand because an estimate solely based on motion of charged particles in magnetic fields can only depend on their rigidity  $E/Z$ . However, the Hillas criterion and Eq. (1) are necessary but in general not sufficient since they do not take into account energy loss processes within the source. Extensions of the conditions on UHECR sources that include energy-loss processes have recently been discussed in Ref. [16]. An interesting argument linking UHECR sources to their luminosity

at radio frequencies has been put forward by Hardcastle [17]. He concludes that if UHECRs are predominantly protons, then very few sources should contribute to the observed flux. These sources should be easy to identify in the radio and their UHECR spectrum should cut off steeply at the observed highest energies. In contrast, if the composition is heavy at the highest energies then many radio galaxies could contribute to the UHECR flux but due to the much stronger deflection only the nearby radio galaxy Centaurus A may be identifiable.

In fact, the Pierre Auger data reveal a clustering of super-GZK events towards the direction of Centaurus A (NGC 5128) [18, 11], whereas other directions on the sky with an overdensity of potential UHECR accelerators such as the Virgo cluster containing the prominent radio galaxy M87 show an apparent deficit in such events [19]. This is somewhat surprising since, although Cen A is the closest radio galaxy and the third-strongest radio source in the sky, it is a relatively weak elliptical radio galaxy [20], making it difficult to reach the required UHECR energies. However, one should note that the UHECR events observed towards Cen A could at least partly originate from sources within the Centaurus galaxy cluster which is located just behind Cen A and is itself part of the Hydra-Centaurus supercluster. In any case, due to its closeness, Cen A has been observed in many channels. For example, its lobes have been detected in 200 MeV gamma-rays by Fermi LAT [21], and its core was observed by Fermi LAT [22]. These observations and its potential role as a major local UHECR accelerator has lead to many multi-messenger model building efforts for Cen A [20, 23]. As an example, in Ref. [23] it was pointed out that proton acceleration in the jet of Cen A is hard to reconcile with Cen A observations in TeV gamma-rays by HESS [24] if gamma-rays are produced by proton-proton interactions. Instead,  $p-\gamma$  interactions in the core are consistent with these observations.

We note in passing that another potential UHECR source are gamma-ray bursts (GRBs) [25]. Although GRBs individually have more than adequate power to achieve the required maximal acceleration energies, but may be disfavored in terms of local power density compared to an UHECR origin in AGNs and radio galaxies.

Another interesting new question concerns the chemical composition of highest energy cosmic rays: The depth in the atmosphere where particle density in the giant air showers observed by the Pierre Auger Observatory is maximal, and in particular the fluctuations of the depth of shower maximum from event to event, when compared with air shower simulations, point towards a heavy composition for energies  $10^{19} \text{ eV} \lesssim E \lesssim 4 \times 10^{19} \text{ eV}$ . At higher energies statistics is insufficient to determine the variance of the depth of shower maximum [26]. On the other hand, HiRes observations are consistent with a light composition above  $\simeq 1.6 \times 10^{18} \text{ eV}$  and up to  $\simeq 5 \times 10^{19} \text{ eV}$  above which statistics is insufficient to determine composition [27]. This could indicate that statistics is still too limited to draw firm conclusions or that the Northern and Southern hemispheres are significantly different in terms of UHECR composition. In addition, there are significant uncertainties in hadronic cross sections, multiplicities and inelasticities that can influence predicted air shower shapes and none of the existing hadronic interaction models consistently describes the shower depth and muon data of the Pierre Auger experiment [28, 29].

Note that the center of mass energy for a UHECR interacting in the atmosphere reaches a PeV =  $10^{15}$  eV, which is still a factor of a few hundred higher than the highest energies reached in the laboratory, at the Large Hadron Collider (LHC) at CERN. It is, therefore, not excluded that the true chemical composition is light on both hemispheres and the UHECR data teaches us something fundamental about hadronic interactions at energies unattainable in the laboratory.

The question of chemical composition is linked to other observables such as the UHECR spectrum. Unfortunately, the current statistics is still insufficient to gain significant information on the chemical composition from the observed spectrum. The flux suppression observed above  $\simeq 4 \times 10^{19}$  eV is qualitatively consistent with either proton or nuclei heavier than carbon up to iron nuclei [30, 32, 33]. In the latter case, the main energy loss process responsible for the “cut-off” is photo-disintegration on the CMB and infrared backgrounds. It should be noted, however, that the observed flux suppression could also be due to the intrinsic maximal acceleration energies attained in the sources, although it would possibly be somewhat of a coincidence that this energy should be close to the GZK energy.

The UHECR chemical composition can in principle also be tested independently with the flux of secondary cosmogenic neutrinos [33, 34, 35] and photons [58, 37]: These secondaries are essentially produced by pion production on the constituent nucleons of a nucleus with a given atomic number  $A$ . Therefore, if the maximal acceleration energy  $E_{\max}$  is not much larger than  $10^{21}$  eV then for mass numbers  $A$  approaching iron group nuclei, the energy of the constituent nucleons will be below the GZK threshold for pion production on the CMB and secondary gamma-ray and neutrino production can only occur by interactions with the infrared background, with a rate suppressed by the relative target photon number density which is a factor of a few hundred. As a result, the cosmogenic neutrino and photon fluxes depend strongly on injection spectrum, maximal acceleration energy and chemical composition, but it may not always be easy to break the resulting degeneracies.

Finally, the question of chemical composition of UHECRs is strongly linked with the question of deflection angles in cosmic magnetic fields. In a field with rms strength  $B$  and coherence length  $l_c$  the rms deflection angle of a cosmic ray of energy  $E$  and charge  $Ze$  traveling a distance  $d$  is given by [38]

$$\begin{aligned} \theta(E, d) &\simeq \frac{(2dl_c/9)^{1/2}}{r_g} \\ &\simeq 0.8^\circ Z \left( \frac{E}{10^{20} \text{ eV}} \right)^{-1} \left( \frac{d}{10 \text{ Mpc}} \right)^{1/2} \left( \frac{l_c}{1 \text{ Mpc}} \right)^{1/2} \left( \frac{B}{10^{-9} \text{ G}} \right), \end{aligned} \quad (2)$$

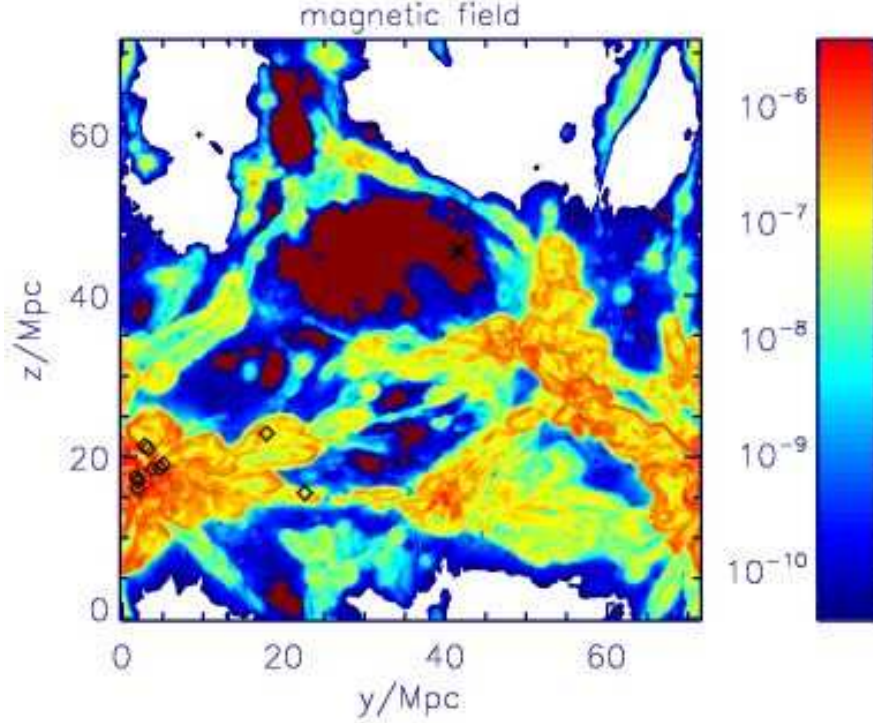
where  $r_L = E/(ZeB)$  is the Larmor radius. For an order of magnitude estimate for the deflection angles in the Galactic magnetic field we use  $l_c \sim 100$  pc,  $d \sim 10$  kpc,  $B \sim 3 \mu\text{G}$  gives  $\theta(E) \sim 1^\circ Z(10^{20} \text{ eV}/E)$ . Thus, protons around the GZK cut-off,  $E \sim 60 \text{ EeV}$ , will be deflected by a few degrees or less, whereas iron nuclei can be deflected by several dozens of degrees. This immediately raises the issue that the Galactic magnetic fields are likely to destroy any possible correlation with the local large scale structure in case of a heavy composition. Detailed numerical simulations

demonstrate that the relatively large deflections of a heavy composition can considerably distort the images of individual sources and even of the local large scale structure as a whole [39].

Large scale extra-galactic magnetic fields (EGMF) are much less well known than Galactic magnetic fields [40]. One reason is that one of the major detection methods for the EGMF, the Faraday rotation of the polarization of radio emission from a distant source which is a measure of the line of sight integral of the plasma density and the parallel magnetic field component, is only sensitive to fields at a given location stronger than  $\sim 0.1 \mu\text{G}$ . Fields below that strength require much higher statistics data than currently available, but still have a strong effect on UHECR deflection, as obvious from Eq. (2). As a statistical average over the sky, an all pervading EGMF is constrained to be  $\lesssim 3 \times 10^{-7} (l_c/\text{Mpc})^{1/2} \text{G}$  [41]. Assuming an EGMF whose flux is frozen and follows the large scale structure gives the more stringent limit  $B \lesssim 10^{-9} - 10^{-8} \text{G}$ , but the fields in the sheets and filaments can in this case be up to a micro Gauss. This is also the scale which is routinely observed in galaxy clusters which are the largest virialized structures in the Universe. Beyond clusters at most hints exist on the EGMF, for example in the Hercules and Perseus-Pisces superclusters [42]. It is expected, however, that in the future large scale radio telescopes such as Lofar and SKA will improve observational information on the EGMF in the large scale structure dramatically. We note in this context that the EGMF in the voids is expected to be very weak and uncontaminated by astrophysical processes. This makes voids excellent probes of relic seed magnetic fields from the early Universe [43]. It is exciting that the non-observation at GeV energies by Fermi of certain distant blazars that were seen at TeV energies by HESS suggest a *lower limit*  $E \gtrsim 3 \times 10^{-16} \text{G}$  on the EGMF in the voids [44]. This is because the TeV gamma-rays seen by HESS would initiate electromagnetic cascades that should be detectable by Fermi unless an EGMF of that strength deflects these cascades into a diffuse halo around the source whose flux is then below the Fermi sensitivity. However, void fields at that level are not relevant for UHECR propagation.

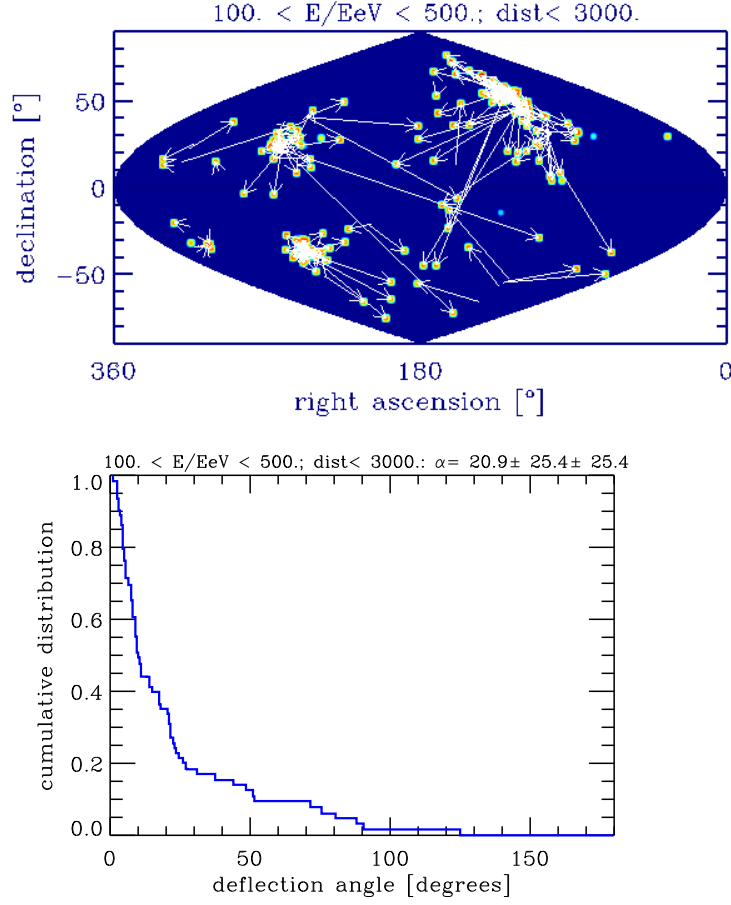
As long as better observational information on the EGMF is not available yet, one way of proceeding is to build models of the EGMF using large scale structure simulations. Two major techniques for doing this are a magnetohydrodynamic version of a constrained smooth particle hydrodynamics code [45] and Eulerian grid-based hydro+n-body codes [46]. The magnetic fields are followed passively and are seeded either uniformly or around cosmic shocks through the Biermann battery mechanism. The normalisation is then constrained by the largest fields observed in galaxy clusters. Alternatively, it has been assumed that the EGMF follows the local vorticity and turbulent energy density of the matter [47]. These numerical approaches agree on the fact that these fields tend to follow the large scale galaxy structure, i.e. the fields tend to be strongest around the largest matter concentrations. A cross section through one of these simulations [48, 49] is shown in Fig. 1 (upper panel). However, they disagree on certain aspects that are relevant for UHECR deflection, most notably the filling factor distributions, i.e. the fraction of space filled with EGMF above a certain strength, as a function of that strength [50]. While this causes considerable differences in the size of the deflection angles predicted between the source and





**Fig. 1** A cross section through a typical large scale structure simulation such as the ones discussed in Ref. [48, 49], on a scale of 70 Mpc in both directions. Ten sources marked with diamonds in the environment of a massive galaxy cluster. The black cross indicates the observer. The color contours represent the magnetic field strength in units of Gauss, as indicated.

the observed events, the deflections tend to be *along and within* the cosmic large scale structure of the galaxy distribution. This can be seen in Fig. 2 where the upper panel shows how the arrival directions relate to the source positions on the sky and the lower panel shows the distribution of the deflection angles between these two directions. In this scenario the deflected UHECR arrival directions tend to follow arc-like structures that result from deflections within the large scale cosmic filaments. In other words, as long as the sources are not very nearby, the EGMF is unlikely to deflect UHECRs out of the large scale structure since the fields in the voids are very small. This means that the overall UHECR arrival direction distribution arriving outside the Galaxy is likely to still correlate with the local large scale structure even in the scenarios with large EGMF, heavy nuclei and large deflection angles, although the events do in general not point back to the sources. On the other hand, since deflections in the Galactic field are unlikely to correlate with extragalactic deflections, large deflections of heavy nuclei in the Galactic field are expected to have a much stronger influence on correlations with the local large scale structure.



**Fig. 2** Upper panel: Simulated arrival directions of UHECR above  $10^{20}$  eV in a scenario where the sources shown in Fig. 1 inject a pure iron composition with an  $E^{-2.2}$  spectrum and equal luminosity up to  $10^{22}$  eV. The density of discrete sources in this simulation is  $\simeq 2.4 \times 10^{-6} \text{ Mpc}^{-3}$  and the maximal distance the primary cosmic rays were allowed to propagate is 3000 Mpc. The arrows point from the source to the detected event. Lower panel: Distribution of deflection angles between arrival direction and source position. The average deflection angle is  $\simeq 21^\circ$  with a scatter of  $\simeq 26^\circ$ .

### 3 Testing fundamental symmetries: Lorentz-invariance and cosmic gamma-rays

Both loop quantum gravity and string theory often break the Lorentz symmetry or realize it in ways different from special relativity. Typically, such effects manifest themselves through new terms in the dispersion relation, the relation between energy  $E$  and momentum  $p$  of a particle of mass  $m$ , that are suppressed by some power  $n$  of the Planck mass  $M_{\text{Pl}}$ ,



$$E^2 = m^2 + p^2 \left[ 1 + \eta \left( \frac{p}{M_{\text{Pl}}} \right)^n \right], \quad (3)$$

where  $\eta$  is a dimensionless number (we use natural units in which the vacuum speed of light  $c_0 = 1$ ). Such terms can modify both the free propagation of particles and their interactions.

The propagation velocity now depends on energy in a different way than in case of Lorentz invariance. In fact, in the relativistic limit keeping only terms to first order in  $m^2$  and  $\eta$ , the group velocity for Eq. (3) is

$$v = \frac{\partial E}{\partial p} \simeq 1 - \frac{m^2}{2E^2} + \frac{\eta}{2}(n+1) \left( \frac{E}{M_{\text{Pl}}} \right)^n \equiv 1 - \frac{m^2}{2E^2} + \delta(E), \quad (4)$$

where  $\delta(E) \equiv \eta(n+1)(E/M_{\text{Pl}})^n/2$  is the deviation from the Lorentz-invariant velocity. For photons,  $m = 0$ , this can lead to arrival time-delays between photons of different energies emitted by GRBs or by flares of active galactic nuclei. Such time delays have indeed been observed from space by Fermi LAT and Fermi GBM in the 10-100 GeV region [51] and from the ground, for example, by the MAGIC telescope above 150 GeV [52]. They have been used to establish upper limits on the Lorentz invariance violating (LIV) terms. For  $n = 1$  these are typically of order one,  $|\eta| \lesssim 1$  [51].

Furthermore, the kinematics of interactions can be modified which typically happens when the LIV terms become comparable to the particle rest mass,  $E \gtrsim E_{\text{cr}} = (m^2 M_{\text{Pl}}^{n-2})^{1/n}$ . As a result, the larger the particle mass the higher the energy at which LIV effects come into play. Therefore, TeV electrons and positrons, but not protons, can be used to constrain  $n = 1$  LIV effects [53], and UHE protons are required to obtain constraints on hadronic LIV terms with  $n = 2$  scaling. A particularly interesting case is superluminal motion which occurs for  $\delta(E) > m^2/(2E^2)$  or  $E > m/(2\delta)^{1/2}$ , where for the general case  $\delta(E)$  is the difference of the LIV term for the particle and the photon: At such energies a charged particle would emit vacuum Cherenkov radiation, similar to the motion of an ultra-relativistic charge in a medium with index of refraction larger than one. The resulting rapid energy loss would imply that particles can not reach such energies in astrophysical environments. Their observation in turn allows to rule out the corresponding LIV parameters.

The arguments above make it clear that LIV effects with  $n \geq 1$  increase with energy. The highest energies in Nature are observed in high energy astrophysics, in particular TeV gamma-ray astrophysics and UHE cosmic rays and neutrinos. There is thus a new field emerging at the interface of quantum gravity phenomenology, string theory and astrophysics. In fact, many of the LIV terms of the form of Eq. (3) have already been strongly constrained [54]. We mention in particular constraints based on the flux suppression feature observed in UHECRs that is consistent with the GZK effect: A tiny Lorentz invariance violation with  $\delta_\pi(E_\pi) - \delta_p(E_p) \gtrsim 5 \times 10^{-23}$  would lead to a significant shift of the GZK feature and would thus be ruled out [55]. In terms of  $\eta$ , for  $n = 2$ , LIV effects should thus be suppressed by a factor  $\gtrsim 10^6$ . LIV can also lead to spontaneous decay, vacuum Cherenkov-radiation

and modified photo-disintegration reactions of very high energy nuclei, thereby influencing UHECR chemical composition. This makes future UHECR composition measurements also relevant for testing Lorentz invariance violation [56].

In the following we will focus on photons for which the most important interaction in an astrophysical and cosmological context is pair production on low energy target photons [57]. The highest energy photons we know should be produced are the ones resulting from the decay of  $\pi^0$  mesons produced by the GZK effect. A certain fraction of the UHECR flux should thus be photons. Due to pair production on the CMB and infrared backgrounds and subsequent inverse Compton scattering of the produced electrons and positrons an electromagnetic cascade develops which quickly shifts the electromagnetic flux below the pair production threshold on the CMB,  $\simeq 10^{15}$  eV. As a result, the expected photon fraction of the UHECR flux is rather small, less than 10% around  $10^{20}$  eV and less than 1% around  $10^{19}$  eV [58]. In fact, only experimental upper limits are currently available consistent with the experimental sensitivity [59].

However, a tiny Lorentz symmetry violation can inhibit pair production such that the predicted UHE photon fraction would be much larger, of the order of 20% for  $10^{19}$  eV  $\lesssim E \lesssim 10^{20}$  eV, because any photon produced by pion production, even at cosmological distances, would only be subject to redshift and thus contribute to the local UHE photon flux. This contradicts the observational upper limits and can thus be used to constrain the LIV parameters in the electromagnetic sector. The resulting constraints are very strong, in fact much stronger than the ones obtained from arrival time dispersion of gamma-rays from GRBs [51]: Typically, for LIV terms suppressed to first order in the Planck scale,  $n = 1$ , values  $|\eta| \gtrsim 10^{-14}$  are ruled out, whereas for second order suppression,  $n = 2$ , values  $|\eta| \gtrsim 10^{-14}$  tend to be constrained [60, 61]. Since such dimensionless coefficients would be expected to be of order one if they are not forbidden by some symmetry, this suggests that LIV is most likely absent altogether at first and second order suppression with the Planck scale.

## 4 Searching for new light states in electromagnetic emission of astrophysical sources

Many extensions of the Standard Model of particle physics, in particular scenarios based on supergravity or superstrings, predict a “hidden sector” of new particles interacting only very weakly with Standard Model particles. Such scenarios do not necessarily only contain Weakly Interacting Massive Particles (WIMPs), new heavy states at the TeV scale and above some of which are candidates for the dark matter, but often also predict Weakly Interacting Sub-eV Particles (WISPs) that can couple to the photon field  $A_\mu$  [62]. The most well-known examples include pseudo-scalar axions and axion-like particles  $a$  and hidden photons that mix kinetically with photons.

Axion-Like Particles (ALPs) are described by a Lagrangian of the form

$$\mathcal{L}_{a\gamma} = \frac{1}{8\pi f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} m_a^2 a^2 = -\frac{1}{2\pi f_a} a \mathbf{E} \cdot \mathbf{B} + \frac{1}{2} m_a^2 a^2, \quad (5)$$

with  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$  the electromagnetic field tensor,  $\tilde{F}^{\mu\nu}$  its dual,  $\mathbf{E}$  and  $\mathbf{B}$  the electric and magnetic field strengths, respectively,  $f_a$  a Peccei-Quinn like energy scale and  $m_a$  the axion mass. In addition, ALPs in general have similar couplings to gluons giving rise to mixing between axions and neutral pions  $\pi^0$ . The actual axion was proposed to solve the strong CP-problem, a problem of phase cancellation in quantum chromodynamics, and exhibits a specific relation between coupling and mass,  $m_a \simeq 0.6 (10^{10} \text{ GeV} / f_a) \text{ meV}$  [63].

A hidden photon field  $X_\mu$  describes a hidden  $U(1)$  symmetry group and mixes with the photon through a Lagrangian of the form

$$\mathcal{L}_{X\gamma} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{\sin \chi}{2} X_{\mu\nu} F^{\mu\nu} + \frac{\cos^2 \chi}{2} m_{\gamma'}^2 X_\mu X^\mu + j_{\text{em}}^\mu A_\mu, \quad (6)$$

where  $X_{\mu\nu}$  is the hidden photon field strength tensor,  $m_{\gamma'}$  the hidden photon mass and  $\chi$  a dimensionless mixing parameter and  $j_{\text{em}}^\mu$  is the electromagnetic current. Typical values for the mixing parameter range from  $\sim 10^{-2}$  down to  $10^{-16}$ .

These couplings to photons can induce many interesting effects that are relevant for astronomy and astrophysics: In the presence of electromagnetic fields, in particular of magnetic fields, photons can oscillate into axions and vice-versa, an effect known as Primakoff-effect [64]. In fact, for a while this possibility was even entertained as a possible explanation of the disturbing observation that the explosions of white dwarfs which can serve as “standard candles” because of their roughly constant explosion energy are dimmer than expected in a decelerating Universe that would otherwise lead to the conclusion that the expansion of the Universe must accelerate [65, 66]. Although meanwhile this possibility is basically excluded because it predicts other signatures, notably distortions of the CMB, which have not been observed [67], photon-ALPs mixing can still play a role at higher energies.

Photons can also oscillate into hidden photons even in vacuum. These oscillations can be modified in the presence of a plasma which gives the photons an effective mass whereas the WISP mass is essentially unchanged. This can give rise to matter oscillations reminiscent of the MikheyevSmirnovWolfenstein effect for neutrino oscillations [68, 69]. In particular, even if the mixing in vacuum is very small, one can have resonant conversions of photons into WISPs within a plasma. Such photon conversions in vacuum and in matter can have effects both within astrophysical sources and during propagation of photons from the source to the observer.

The coupling of WISPs to photons and (in case of axions) also to fermions can have an influence on the evolution and structure of astrophysical objects. Due to their weak coupling to ordinary matter, once produced, these hidden sector particles can leave most objects without significant reabsorption, providing an efficient cooling mechanism. This has lead, for example, to strong limits on axion masses and couplings from the requirement that core-collapse supernovae should not cool much faster than predicted if their cooling is dominated by neutrino emission, in

order to be consistent with the few neutrinos observed from the cooling phase of SN1987A [70].

Even if the physics of the astronomical objects is not significantly modified, the photon rates and spectra observable at Earth can be influenced either within the source or during propagation to the observer. A sensitive probe of photon-WISP oscillations requires an as detailed an understanding of the emission process as possible. In this context, one of the best understood radiation sources in the Universe is the cosmic microwave background (CMB). Its spectrum deviates from a perfect blackbody by less than  $\simeq 10^{-4}$ , distortions that have been measured by the COBE-FIRAS experiment [71], and whose deviations from isotropy are of the order of  $10^{-5}$  and have themselves been measured at the percent level by WMAP [72]. This radiation essentially comes from the surface of last scattering, at a distance of a Hubble radius today, and any photon-WISP mixing at a level of  $\sim 10^{-4}$  would induce a spectral distortion or an anisotropy in conflict with the observations. This has lead to some of the strongest limits on the parameters of Eqs. (5) and (6): For  $10^{-9} \text{ eV} \lesssim m_a \lesssim 10^{-4} \text{ eV}$  one has  $f_a \gtrsim 10^{11} (B_{\text{rms}}/\text{nG}) 10^{10} \text{ GeV}$  which strengthens to  $f_a \gtrsim 10^{12} (B_{\text{rms}}/\text{nG}) 10^{11} \text{ GeV}$  for  $10^{-14} \text{ eV} \lesssim m_a \lesssim 10^{-11} \text{ eV}$  [73]. Since photon-ALP mixing requires the presence of a magnetic field, the absence of significant effects on the CMB imposes an upper limit on the combination  $B_{\text{rms}}/f_a$ , with  $B_{\text{rms}}$  the rms large scale extra-galactic magnetic field. Furthermore, requiring the distortions of the CMB induced by photon-hidden photon mixing to be smaller than the COBE-FIRAS limit leads to a bound on the mixing angle  $\chi \lesssim 10^{-7} - 10^{-5}$  for hidden photon masses  $10^{-14} \text{ eV} \lesssim m_\gamma \lesssim 10^{-7} \text{ eV}$  [74]. In contrast to the case of ALPs, these constraints only depend on the vacuum mixing angle  $\chi$  since no external magnetic fields are necessary for photon-hidden photon mixing.

Most other astrophysical sources are non-thermal in nature and thus much less well understood. This is the case in particular for X-ray and gamma-ray sources. Still, if the photon spectra from these objects can be well approximated by power laws, photon-ALPs mixing can induce steps in the spectra that may be detectable. Depending on the strength of magnetic field within the sources, for ALP masses  $m_a \sim 10^{-6} \text{ eV}$  significant effects on spectra between keV and TeV energies can occur for  $f_a \lesssim 10^{13} \text{ eV}$  [75, 76]. These effects are complementary and potentially more sensitive compared to more direct experimental bounds the best of which come from *helioscopes*: Photons from the sun are converted to ALPs in the solar magnetic field which in turn can be reconverted to photons in an artificial magnet in front of a telescope on Earth which then detects these photons. For  $m_a \lesssim 0.02 \text{ eV}$  the CERN Axion Solar Telescope (CAST) experiment provided the strongest constraint,  $f_a \gtrsim 10^{10} \text{ GeV}$  [77].

Since photon-ALP mixing is energy dependent, ALP signatures are best revealed when comparing luminosities at different energies. In particular, it has been pointed out that the *scatter* of correlations of luminosities in different energy bands deviates from a Gaussian if photon-ALP mixing occurs. In fact, considerable deviations from Gaussian scatters have recently been found in the correlations between the luminosities of AGNs in the optical/UV and X-rays [78]. If these sources are located in galaxy clusters which are known to contain magnetic fields of micro Gauss

strength, photon-ALP mixing could explain this observation if  $m_a \ll 10^{-12}$  eV and  $f_a \lesssim 10^{10}$  GeV. In this case, almost energy independent photon-ALP mixing would occur at energies above  $\simeq 2$  keV, whereas the mixing would be highly energy dependent at energies  $\ll 0.5$  keV, thereby inducing non-Gaussian correlations. Similar effects would occur with photon-ALP conversion in magnetic fields within AGNs if  $m_a \ll 10^{-7}$  eV and  $f_a \simeq 3 \times 10^8$  GeV. It has been pointed out, however, that the scatter in the correlation between optical and X-ray luminosities observed in AGNs can also be explained by X-ray absorption [79].

Another possible signature for photon mixing with a new light state has been discussed in the context of high energy gamma-ray observations by the ground-based telescopes MAGIC, H.E.S.S., VERITAS and CANGAROO-III. The absorption of such gamma-rays in the infrared background appears weaker than expected based on models for the infrared background [80, 81], although this is currently inconclusive [82, 83]. If gamma-ray absorption is indeed weaker than computed for the real infrared background, this could be explained if part of the gamma-rays are converted into ALPs around the source which in turn are reconverted into gamma-rays in the Galactic magnetic field [84]. This works for ALP parameters  $10^{-10}$  eV  $\lesssim m_a \lesssim 10^{-8}$  eV and  $f_a \sim 10^9$  GeV. Alternatively, conversion and re-conversion could be induced by the EGMF if  $m_a \lesssim 10^{-10}$  eV and  $5 \times 10^{10}$  GeV  $\lesssim f_a \lesssim 10^{18}$  GeV [85, 86]. A recent detailed study on these effects has been performed in Ref. [87]. We note, however, that an apparently reduced absorption of  $\gamma$ -rays from high redshift sources can also be explained if these  $\gamma$ -rays are produced near Earth by primary TeV-PeV *cosmic rays* from the same source which interact much less frequently with the low energy target photons than TeV  $\gamma$ -rays [88]. This is possible provided that cosmic ray deflection is sufficiently small, corresponding to large scale EGMFs of strength  $B \lesssim 3 \times 10^{-14}$  G [89].

## 5 Conclusions

In this contribution we have discussed three examples in which astronomy plays an interdisciplinary role at the intersection with the neighboring scientific fields of cosmology and particle physics: The nature and origin of the highest energy particles observed in Nature, tests of the Lorentz symmetry which is one of the pillars of modern science tiny breakings of which may yield fundamental insights into Nature and may lead to observable effects at the highest energies, and, at the opposite end of the energy scale, the mixing of photons with new light states such as axion-like particles or hidden photons. While this list is certainly not exhausting and does not include other important topics such as the search for dark matter, it hopefully gives an idea about the role of interdisciplinarity in astronomy. With the first results coming in from the Large Hadron Collider, the most powerful existing particle physics experiment in terms of energy and luminosity, new levels of cross-fertilization between astronomy and particle physics are expected for the near future.

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